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Research article

Forecasting seasonal peaks in roadkill patterns for improving road management

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ABSTRACT

For several species, roadkill is not spatially aggregated on hotspots, having instead a more diffuse pattern along the roads. For such species, management measures such as road passages may be insufficient for effective mitigation, since a large part of the road crossings is likely to occur outside the influence of those structures. One complementary approach could be to implement temporary mitigation actions, such as traffic calming. This requires understanding when roadkill peaks may occur. We tested the feasibility of predicting seasonal peaks of roadkill using data from a 3-year systematic monitoring (78 surveys over ca. 960 km of roads) from eight non-flying vertebrate species from Mato Grosso do Sul, Brazil, with different body size and life history traits (ca. 6400 records from focal species). We modelled the time-series of the roadkill of these species at large scale (state level) using generalized additive mixed models (GAMMs). We used the data of the first 2 years as training datasets, and the information from the third year of surveys as testing datasets to evaluate the prediction performance of models. Overall, the models of species feed with a higher number of records were able to follow reasonably well the variations of roadkill over time, although they were not able to correctly predict the number of collisions. For species with fewer observations, the models presented a poorer goodness-of-fit and prediction ability. Our results suggest that, at least for those species with higher roadkill rates, it can be possible to forecast periods of higher probability of occurring hot-moments of mortality. Such models can provide valuable information to implement seasonal management actions.

1. Introduction

Roads are the most conspicuous infrastructure in the landscapes of most countries, affecting biodiversity patterns and ecological processes (Ibisch et al., 2016; Laurance and Balmford, 2013; Maxwell et al., 2016). Of all road-related direct impacts, roadkill is probably the most harmful to wildlife (Forman and Alexander, 1998; Van der Ree et al., 2015). Billions of animals of numerous species are road-killed every year, with impressive estimates around the world reaching 2.2 million mammals on Brazilian roads (González-Suárez et al., 2018) and 29 million mammals in Europe (Grilo et al., 2020). Virtually all species inhabiting road vicinity areas are impacted by road mortality, which effect may ultimately lead to local population depletion (Ascensão and Desbiez, 2022; Barrientos et al., 2021).

Understanding the patterns and drivers that lead to higher/lower roadkill rates may thus provide valuable information for mitigation planning and management (Ascensão et al., 2019; Lesbarrères and Fahrig, 2012; Rytwinski et al., 2016). Several studies have focused on understanding the main factors that shape the spatial patterns of roadkill and where they were more likely to occur i.e., hotspots of mortality (Ascensão et al., 2017; Mayer et al., 2021; Russo et al., 2020). This information is important as road mitigation is largely based on the implementation of fixed structures, such as over and under passages, or the upgrading of existing passages, such as culverts, to improve the

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permeability of roads (Lesbarrères and Fahrig, 2012; Rytwinski et al., 2016). Yet, for several species, the spatial patterns of mortality along the roads do not show clear and consistent patterns of hotspots, having diffused mortality pattern (Ascensão et al., 2017; Santos et al., 2017). For these species, the implementation or improvement of passages may be insufficient for effective mitigation, since a large number of road crossings and consequently of their road mortality is likely to occur outside the influence of those structures.

On the other hand, implementing permanent large-scale mitigation measures, such as traffic calming, over long stretches of roads may not be effective and would likely become unpopular in the eyes of citizens. Such measures may preferentially be applied during short periods, when there is a higher probability of having a high number of road crossings. Numerous studies have reported significant temporal peaks of roadkill for several species (e.g., Ascensão et al., 2019; Cureton and Deaton, 2012; Gonçalves et al., 2018; Raymond et al., 2021), and such peaks of mortality are likely related with species' phenology and their relation to climate conditions. These relations are likely to promote fluctuations in species occurrence or abundance of the populations (e.g., due to reproduction or migratory events), and affect individual movement (e.g., mating or dispersal events) in road vicinity areas throughout the year. In turn, such fluctuations are related to the variation of roadkill rates over time (Beaudry et al., 2009; Mayer et al., 2021; Raymond et al., 2021). Thus, if one could predict when seasonal mortality peaks are more likely to occur, it could be possible to plan and implement short-term temporary road management actions aiming to reduce the likelihood of roadkill. Such an approach may be particularly effective for species with a generalized distribution, for which static mitigation measures may serve only a small proportion of the existing population in the surroundings of the roads.

Here, we tested the feasibility of predicting peaks of roadkill using the data from a large-scale assessment over Mato Grosso do Sul, Brazil. We focused on eight non-flying vertebrate species with quite different body size and life history traits, aiming to embrace a large diversity of animals highly impacted by road mortality. We expected to successfully model the roadkill numbers in such a way that one could forecast when peaks of mortality could occur i.e., hot-moments of roadkill. If so, it could improve our ability to avoid a high proportion of collisions by implementing temporal mitigation measures, complementary to static mitigation, with benefits for biodiversity as well for human safety and vehicles (Ascensão et al., 2021).

2. Methods

2.1. Study area and roadkill information

Roadkill information was obtained from the 'Anteaters & Highways' project (www.giantanteater.org), which has collected information of roadkill rates over a large spatial extent across the Mato Grosso do Sul state, Brazil (Fig. 1). Systematic surveys were carried out every two weeks in paved roads (BR-262, BR-267 and MS-040, ca. 960 km; Fig. 1) throughout the state, between February 2017 and February 2020 (79 surveys). Monitoring was made by car at a 40–60 km/h speed, searching for carcasses on both road lanes and shoulders. Location of carcasses were obtained with hand-held GPS before carcasses removal.

The land use was dominated by open areas (grassland, pasture, and agriculture), followed by remnant native forest vegetation (Fig. 1). Urban areas had relatively low representation in the study area and were not included in road transects. The traffic volume was similar across transects in the federal roads (BR-262 and BR-267) surveyed, ca. 3600 vehicles per day (DNIT, 2020). In state road MS-040, the traffic is estimated to be much lower, ca. 653 vehicles per day (Ascensão et al., 2021). The climate throughout MS is wet from October to March and dry from April to September (Koppen's As or Aw), with mild year-round temperatures (range 21–32 °C). The average annual rainfall ranges between 1000 and 1500 mm.

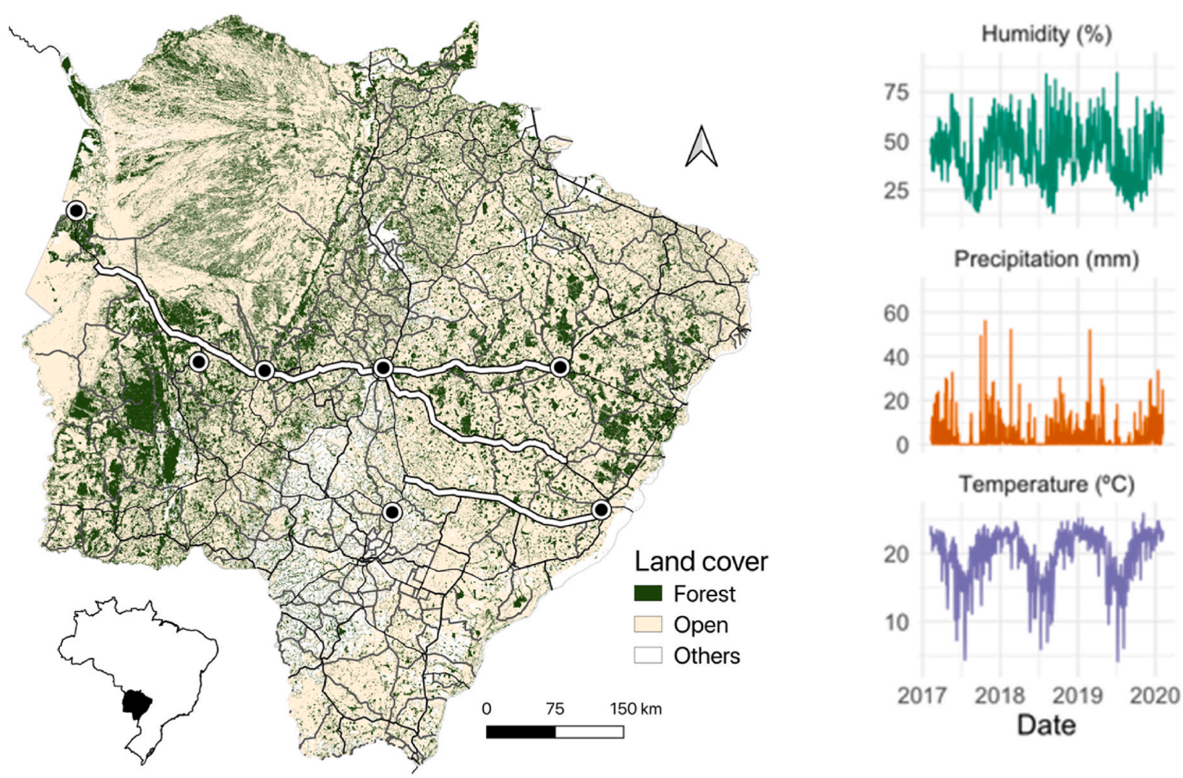

Fig. 1. Location of surveyed roads (double lines) and weather stations (circles) in Mato Grosso do Sul state (state location in Brazil on the left), and main land cover classes. Other road network is depicted as dark lines. Right panel: time-series of climate information used for modelling purposes.

2.2. Focal species

Our focal species included the Argentine black and white tegu (*Salvator merianae*), yacare (*Caiman yacare*), nine-banded armadillo (*Dasypus novemcinctus*), six-banded armadillo (*Euphractus sexcinctus*), southern tamandua (*Tamandua tetradactyla*), giant anteater (*Myrmecophaga tridactyla*), capybara (*Hydrochoerus hydrochaeris*), and crab-eating fox (*Cerdocyon thous*). These species are amongst the top road-killed in our study area (Ascensão et al., 2021). The dataset contained 238 tegus, 825 yacares, 704 nine-banded armadillos, 1702 six-banded armadillos, 503 southern tamanduas, 523 giant anteaters, 514 capybaras, and 1430 foxes. Overall, given their generalist nature, the road mortality of these species is spread along the roads crossing their area of occurrence, without well-defined hotspots of mortality (Ascensão et al., 2017, 2021).

The yacare is widely distributed in Pantanal, being able to travel long distances searching for water during the dry season (Campos et al., 2006; Campos and Magnusson, 2011). The tegu is a lizard that inhabits the tropical rain forests, savannas, and semi-deserts of eastern and central South America. Like other reptiles, tegus go into brumation when the temperature drops, but exhibit a high level of activity during their wakeful period of the year (Toledo et al., 2008). Both armadillos breed throughout the year and are present in a variety of habitats, but the nine-banded armadillo prefers forested areas while the six-banded armadillo mainly occurs in open areas, savannas and shrublands (Bonato et al., 2008; Desbiez et al., 2010; Ferreguetti et al., 2016). A similar pattern is observed in the two anteaters species habitat preference, with the southern tamandua more frequently associated with forested areas and the giant anteater most frequently found in opened or savannah areas (Desbiez and Medri, 2010). Moreover, the giant anteater presents a spatial pattern more dependent on its own thermoregulation varying between open and closed areas (Giroux et al., 2021). The capybaras have a wide distribution in many areas of Brazil, although the species shows preferences for environments close to water and natural grasslands (Lopes et al., 2021). Capybaras are one of the largest mammals in Brazil, having a very wide distribution, therefore representing a threat to human safety on the roads (Abra et al., 2019). Finally, the crab-eating fox have one of the most conspicuous distributions of the listed mammals and seems to tolerate different habitat (Faria-Corrêa et al., 2009).

2.3. Environmental variables

For modelling purposes, we gathered daily climate information from the nearest weather stations in Mato Grosso do Sul (data retrieved from CEMTEC, URL: www.cemtec.ms.gov.br; Fig. 1), including precipitation, minimum and maximum humidity, and minimum and maximum temperature. The climatic variables were averaged per day across weather stations, representing the climatic conditions on the road surrounding areas along time (Fig. 1).

2.4. Data analysis

Before analysis, all variables were screened for multicollinearity using Pearson's correlation analysis. There was evidence of high correlation (>0.70) between both humidity values as well between both temperature values, so we discarded maximum humidity and maximum temperature from subsequent analysis. As the roadkill surveys were carried out with an interval of two weeks, some of the carcasses found could be from collisions that occurred in the previous days, before the survey date. Thus, the climatic conditions associated with the number of roadkills observed may have occurred in the previous 15 days, although with a lower probability for longer time lag due to the corresponding lower probability of carcass persistence (Santos et al., 2016). As so, we built three datasets averaging the climatic information from the last 3, 5 and 10 days prior to each survey date (hereafter '3 d', '5 d', and '10 d', respectively).

We divided the full roadkill dataset into two parts, the first containing the data from the first two years, which was used as the training dataset, and the second containing the information from the third year of surveys, which was used as the testing dataset, to evaluate the prediction performance of models. We applied generalized additive mixed models (GAMMs) to analyze and model the roadkill data. GAMMs were fitted using the information of the three climate predictors (precipitation, humidity, and temperature), together with a smooth term on month using a cycle cubic regression spline with 12 knots. 'Road' was treated as a random effect to consider among-road variation regarding their land use and other intrinsic characteristics that could influence variable animal abundance between road vicinity areas. We further included an autocorrelation-moving average correlation structure (ARMA) to account for temporal autocorrelation of records, using month as grouping factor. The ARMA structure requires two parameters specifying the autoregressive order (p) and the moving average order (q). For each focal species, we built separate models relating the number of roadkill (N_{RK}) and predictors using all combinations of environmental datasets (i.e., '3 d', '5 d', and '10 d') and ARMA terms (p and q; both varying between 1 and 3). GAMM were fitted using the 'mgcv' R package (Wood, 2011, 2017), with the general structure (following the R language):

```
mgcv::gamm(NRK ~ Precipitation + Humidity + Temperature + s(Month, bs = "cc", k=12) + s(Road, bs="re"), correlation = corARMA(form
= ~ 1|Month, p=p, q=q), method = "REML", family= "poisson")
```

For each species, all models were ranked according to the Akaike Information Criterion (AIC), and we retained the model having the lowest AIC. We then predicted for the third year (testing dataset) the expected number of roadkills of each species based on the best models. Confidence intervals of fitted and predicted values were based on 2000 replications.

The goodness-of-fit of models was assessed using the squared of correlation values between observed and fitted values (R^2). High R^2 values shows that the model's variance is similar to that of the true values, whereas a low R^2 suggests that the two values are not strongly related. The predictive performance was evaluated using the Mean Absolute Percentage Error (MAPE), a measure of prediction accuracy of a forecasting model, which is the sum of the absolute error normalized by the sum of the realized values:

$$MAPE = \frac{\sum_{t=1}^{n} |Obs_t - Pred_t|}{\sum_{t=1}^{n} |Obs_t|}$$

where *Obs* is the observed data and *Pred* is the predicted values, for the different t times. Lower MAPE values indicate a higher predictive accuracy of the model.

We then compared the obtained R^2 and MAPE values with the ones obtained by randomizing (n = 1000) the estimated values, per road. This procedure gave us a measure of the departure of R^2 and MAPE values from a random distribution (for each road). We further checked for autocorrelation of model residuals. If present, it could suggest that some

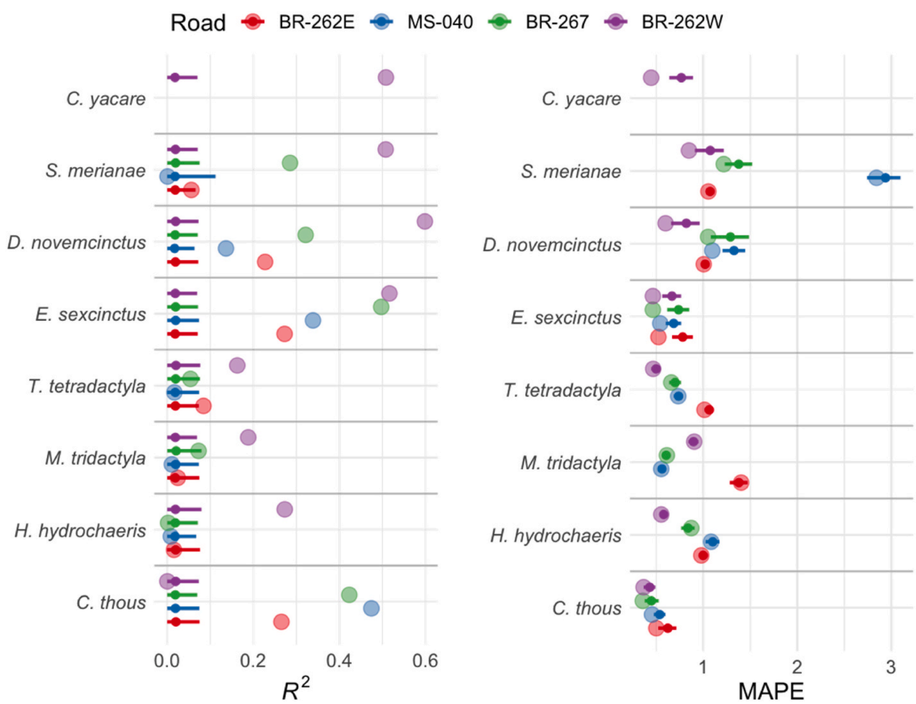

Fig. 2. Evaluation of time-series models relating observed and estimated road mortality of the eight focal species. Left panel: the goodness-of-fit of models was measured using R^2. Right panel: the predictive performance was evaluated using the Mean Absolute Percentage Error (MAPE). For each indicator, species, and road, we compared the observed estimate with a series of randomizations (n = 1000), from which we obtained the mean and 5%–95% percentiles. Estimates outside that interval were considered significant.

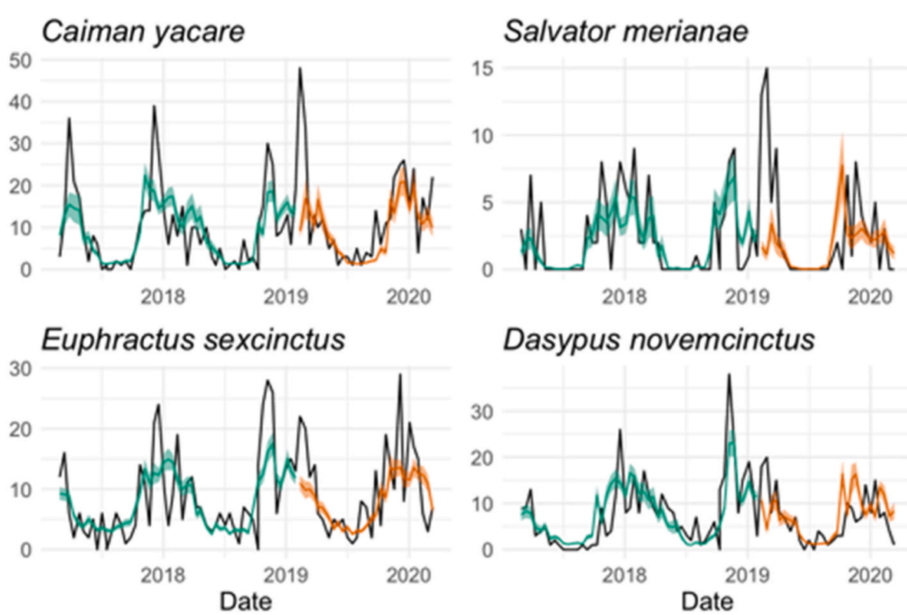

Fig. 3. Observed (black line), fitted (green) and predicted values (brown) with respective 90% confidence interval (CI) according to the most parsimonious time-series models relating roadkill with climate variables. Presented are the results for road BR-262 west, for those species which GAMM had best goodness of fit (higher R^2) and best predictive performance (lower MAPE). Predictions and CI were based on 2000 replications. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

serial correlation or seasonality was not properly been integrated by the models. All analysis and plots were made in R (R Development Core Team, 2020).

3. Results

The most parsimonious models for the distinct species included different combinations of the climate datasets and ARMA parameters (the combination across species is presented in Supplementary material S1). The models using the training dataset showed levels of R^2 ranging between 0.00 and 0.60, suggesting a reasonable fitting ($R^2 > 0.50$) for both reptiles and both armadillos on Road 'BR-262 west' (Fig. 2). The fitted values of these species followed reasonably well the observed values (Fig. 3), whereas for the other species, in particular for capybara and both anteaters, the fitting was less defined (Supplementary material S2). Regarding the ability of models to predict roadkill numbers, the models that presented the best performance (i.e., lower MAPE) were again those of both reptiles and armadillos, particularly for road 'BR-262 west' (Fig. 2). Interestingly, for these species, the models could clearly accompany the seasonal variation of roadkill numbers, i.e., models could roughly forecast the upcoming periods of greater number of roadkills (Fig. 3). The models of the other species had lower performance values, but R^2 was generally significantly different from the randomized distribution (Fig. 2). For example, the fitted values of the fox model could also accompany the seasonal variation of roadkill numbers across roads, although the predictive performance was relatively lower (Supplementary material S2). There were no obvious signs of autocorrelation in the different models (see Supplementary material

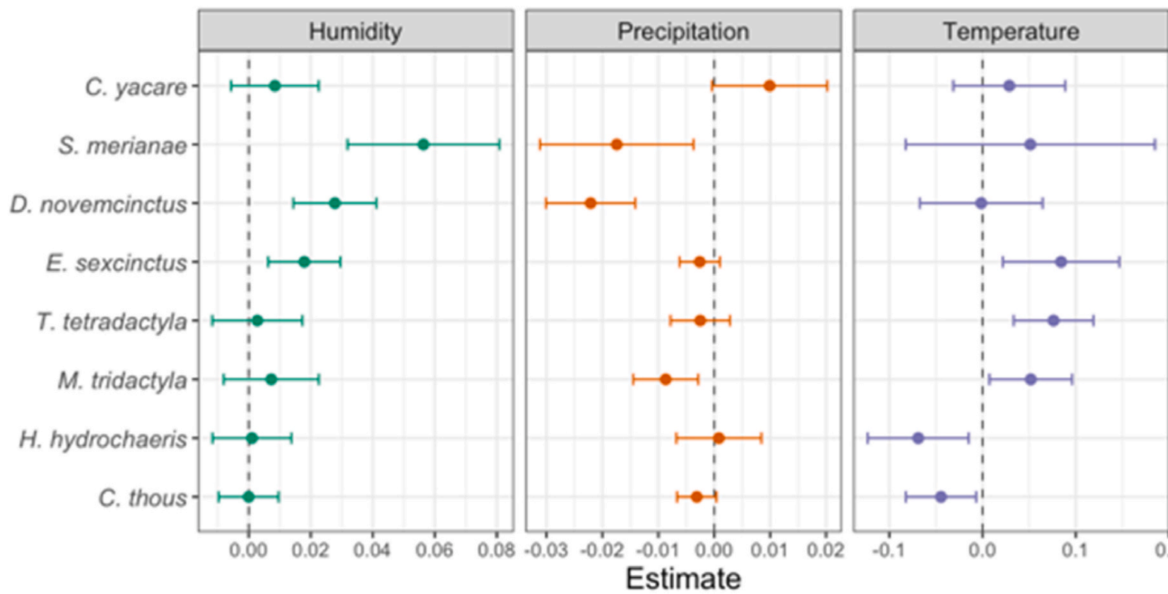

Fig. 4. Estimates and 95% confidence intervals for the climatic predictors used to model the time-series of roadkill for the eight focal species.

S3).

Concerning the effect of environmental variables, the humidity was significantly and positively related with the mortality of tegu and both armadillos; the effect of precipitation was significant and negative for tegu and nine-banded armadillo, as well for giant anteater; and temperature, was significantly and positively related with the roadkill numbers of six-banded armadillo and both anteaters, and negatively with the mortality of capybara and fox (Fig. 4).

4. Discussion

We tested whether we could model and forecast the variations of roadkill overtime for eight species with quite different characteristics, thus embracing a large diversity of animals inhabiting the study region. Our focal species, two reptiles and six mammals, are among the top road-killed animals on the roads of the region, but their collisions are widespread along the roads i.e., without clear concentrations or hotspots (Ascensão et al., 2017, 2021).

Our results suggest that, at least for some species with sufficient data, it is indeed possible to model the time-series of roadkill, and consequently that it is possible to forecast the upcoming of periods with higher probability of occurring a large number of collisions i.e., hot-moments of roadkill. We were able to build models that predicted the mortality peaks with a reasonable degree of certainty for both reptiles and both armadillos, and to a lesser extent for the fox. For these species, the road mortality had clear seasonal peaks, which were captured by the respective models. Previous studies have reported the existence of hot-moments of roadkill for several species (D'Amico et al., 2015; Garriga et al., 2017; Gonçalves et al., 2018; Mayer et al., 2021), and we show that such patterns can be modelled using climatic-based time-series models. On the other hand, those models with poorer predictive performance were those in which the number of records was lower, and the species showed no clear patterns of roadkill along time i.e., without clear hot-moments of mortality, as capybara and both anteaters.

In general, well-defined patterns of seasonal mortality were related to climatic variables. This relation probably stems from the fact that the phenology of the species is influenced by climatic conditions, with different seasonal activity, namely movement and abundance (e.g., mating and reproduction), leading to a greater number of crossings and, consequently, of roadkill (Ascensão et al., 2019; Cureton and Deaton, 2012; Garrah et al., 2015). For example, the mortality pattern of yacare suggests a higher likelihood of collisions with this species during summertime and rainy periods. This may be related with the fact that the caiman disperses through the floodplain during summer, looking for new ponds (Campos et al., 2006; de Souza et al., 2015). Likewise, the tegu is inactive almost half of the year, with the active period in the warm months, when they move to reproduce and to forage (Toledo et al., 2008), probably increasing the probability of crossing roads and being road-killed. The relation of humidity with the mortality of both armadillos may be related with their physiological constraints and limited thermoregulatory capabilities, likely to restrict their activity during colder periods (Maccarini et al., 2015). Conversely, the peak of mortality of fox coincided with colder periods, when juveniles and sub-adults are likely to disperse (Faria-Corrêa et al., 2009). We do not have data on the local abundance of our focal species, so we could not make a relationship between the variation in mortality on the roads and the abundance of species in road surroundings. Future research should therefore strive to collect abundance information along time, which could greatly improve our ability to predict peaks of roadkills (D'Amico et al., 2015).

Our study supports previous research calling for a mixed approach of road management to reduce roadkill of wildlife (e.g., Gonçalves et al., 2018). The ability to forecast and anticipate hot-moments of mortality on the roads may provide valuable information to implement short-term seasonal mitigation measures. Such measures include the speed reduction, for example by using speed control radars and speed bumps together with proper warning signage (Hobday and Hobday, 2010; Rytwinski et al., 2016; Sullivan et al., 2004). Ultimately, some road stretches can be closed to traffic, at least during the peak hours of animal activity, for example in areas of higher landscape connectivity. These measures could complement static mitigation measures, namely road fencing and passages. In our study area, existing bridges and drainage culverts along the roads can be improved and linked to fences, to increase their use by animals, avoiding several crossings through the road pavement. Yet, given the widespread mortality patterns of our focal species, the upgrade of the existing passages may not suffice to significantly reduce their mortality rate. Hence, the mixed approach of spatial (permanent) and seasonal (temporary) mitigation, may help reducing a large proportion of collisions, with benefits for wildlife and people. For example, in Brazil, most collisions with large animals occur during nighttime, causing significant losses of human lives and vehicle damage (Abra et al., 2019; Ascensão et al., 2021).

It should be noted that the road mortality of species such as the giant anteater reach concerning rates in our study area (Ascensão et al., 2017, 2021). Their mortality patterns lack clear concentrations, both spatial and temporal. Likewise, other species of conservation concern also lack clear concentrations of mortality, including the giant armadillo (*Priodontes maximus*) and jaguar (*Panthera onca*). For these species, both static mitigation and temporal road management measures may not effectively reduce the impact of roadkill. Therefore, mitigation measures tailored to these species should be considered, namely, offsetting areas of habitat devoid of roads.

5. Conclusions

In conclusion, our study adds information on how to improve road management guidelines toward the reduction of wildlife roadkill. For species showing more regular temporal patterns of roadkill fluctuations, it is possible to model such patterns and forecast peaks of mortality. Such information can be used to inform when to implement road management actions, namely traffic slowdown of even temporary road closure.

Authors' contributions

DRY and **ZC** collected the data; **FA** developed the methods, performed the data analysis; **YGGR** and **FA** prepared the first draft of the paper. **FA**, **YGGR**, **ZC**, **DRY** and **ALJD** contributed to the design of the research, discussed data, and contributed to writing the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115903.

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